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RECOMMENDATIONS FOR SHIP HULL SURFACE REPRESENTATION.(U)

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UNCLASSIFIED NPS-53-80-001 NL

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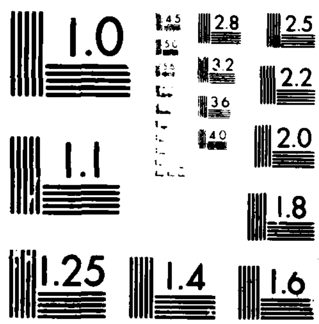
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(14) NPS53-80-001

NAVAL POSTGRADUATE SCHOOL

Monterey, California

(6) RECOMMENDATIONS FOR SHIP HULL SURFACE REPRESENTATION

by

(10) Richard Franke

(11) Feb[redacted]80 (12) 20

(9) Final Report for Period

Apr[redacted]— May [redacted]79

Approved for public release; distribution unlimited

Prepared for:
Naval Sea Systems Command
Washington, DC 20362

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

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ABSTRACT

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NPS53 - 80 - 001	2. GOVT ACCESSION NO. AD-A084 031	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Recommendations for Ship Hull Surface Representation		5. TYPE OF REPORT & PERIOD COVERED Final, April 1979-May 1979
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Richard Franke		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Mathematics, Naval Postgraduate School, Monterey, CA 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command, Washington, D.C. 20362		12. REPORT DATE 7 Feb 1980
		13. NUMBER OF PAGES 23
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

ship hull representation, ship design, interactive graphics, splines, spline curves, spline surfaces, parametric splines

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1.0 Introduction

The purpose of the present task was to undertake a study which would survey current and proposed schemes for the mathematical representation of ship hulls and to recommend the one(s) which appears to be most promising for improving or replacing current methods in use by the U.S. Navy. To achieve this purpose a large amount of literature was surveyed (see Bibliography) and a number of experts in this and related fields were sought for their views, advice, and other comments. The investigator expresses his appreciation to those persons: Michael Aughey, David Byers, James Claffey, Arthur Fuller, Nathan Fuller, Thomas Gallagher, Robert A. Johnson, Thomas Sauer, and Lewis Smith, all of the Naval Sea Systems Command (NAVSEA), John Daidola of M. Rosenblatt and son; Michael Saboe of Advanced Marine Enterprises; William Helming of Advanced Technology; Tom Corin, Elizabeth Cuthill, James McKee, and Feodor Theilheimer of the David W. Taylor Naval Ship Research and Development center (NSRDC); David Rogers and Willard Roloson of the Naval Academy and F. C. Munchmeyer of the University of Hawaii. Special thanks are due to Nathan Fuller who arranged many contacts when I visited NAVSEA, and Tom Corin who made arrangements for my visit to NSRDC. All of the above have influenced the direction of this investigation, although the investigator is responsible for the conclusions which are drawn.

The following is a brief summary of the investigator's conclusions and recommendations. (1) Most importantly, a ship hull must be represented by a surface. During the detail design phase, designers may require the exact location of any point on the surface. Representation by lines is ambiguous in this respect. Further, the use of lines

requires refairing as more body plans and waterlines are added, thus changing (slightly, one hopes) the definition of the hull. (2) The fairing process must be done interactively. Experience has shown that while most of the process can be achieved using a batch system, the final stages often involve manual intervention. (3) Accomplishment of (2) in a satisfactory manner requires the acquisition of suitable computer equipment and sophisticated interactive graphics displays. This equipment must allow for real time rotation, translation, and scaling in three dimensions. Graphics table input and zoom capability will enable the matching of data and fairing process to be carried out interactively. (4) Personnel capable of implementing the necessary computer codes are on board at NAVSEA. Their time must be made available for such a project, of course.

2.0 Brief Summary of Ship Hull Definition Schemes

Historically, ship hulls have been represented by a series of cross sections of the hull. The usual lines are vertical cross sections perpendicular to the length of the ship (body plans), horizontal sections (waterlines), and vertical cross sections parallel to the length of the ship (buttocks). Other lines may be inspected, especially cross sections parallel to the length of the ship at an angle between vertical and horizontal (diagonals). For construction purposes a preliminary set of lines with the appropriate ship characteristics (e.g., various coefficients relating to basic shape of the hull, center of buoyancy, various moments) would be supplied to the builder. These would then be "faired" at large scale (1/10 scale up to full scale, say) by loftsmen using batten,

or mechanical splines, in a painstaking process involving successive adjustment of body plans and waterlines to obtain a "fair" ship hull which maintained the desired characteristics. Other lines would also be checked for fairness, and the process terminated when the entire set of lines was declared to be fair by the loftsman. To avoid changing the ship characteristics it was necessary to avoid large deviations from the original set of lines. The notion of fairness used by the loftsman is one which seems to defy quantitative description, and opinions as to whether a given set of lines is fair varies from one loftsman to another.

Attempts to detail to the computer the lengthy task of fairing the ship lines has generally (not always) proceeded along the direction of simulating the process used by the loftsmen. Thus, the lines have often (not always) been represented by piecewise polynomials, often (not always) of degree three, since this is the mathematical analogue of the mechanical spline, given certain assumptions. A history of schemes available prior to 1971 is given in the A. D. Little report [5], while later developments are detailed in various proceedings, [7], [16], and [27]. The mathematical definition of fairness used in various schemes is quantified, of course, and although it may differ from one scheme to another, there is general agreement that the second derivative (or curvature) is prominently involved.

While the use of lines for representation of ship hulls has a very long history, practically speaking their use also involves problems. The most serious problem is the fact that insertion of a new body plan and a new waterline may result in nonintersecting curves. This may be overcome by requiring that the new body plan (or waterlines, whichever

comes first) become part of the definition. This quickly leads to large and expanding sets of data and leads to unfair lines as well. For aesthetic as well as practical purposes, it is desirable to define the ship hull as a surface.

There are a large number of computer programs for aiding in the ship design and construction process. These are mentioned briefly in the study reports [38] and [39], and cover varied ranges of the process. Programs which involve the definition of the hull include CASDOS, AUTOKON, STEERBEAR, BRITSHIPS, FORAN, VIKING, and NASD. In the U. S. Navy use is made of HULGEN and HULDEF. Several of these programs are more closely allied with the generation of instructions for numerically controlled cutting and milling than the design process, and thus involve the hull definition from that aspect. This is particularly true of those in use at shipyards. A number of the programs are not well documented, and those that are proprietary are not well documented in the public domain, at least. With the exception of CASDOS and HULGEN, the above are all (apparently) based on the use of lines. HULGEN is a preliminary design tool. Hull surface definition in CASDOS is based on Coon's patches and the program has been used in the detail design of four LSD vessels. Unfortunately, the implementation contained several errors which resulted in a great deal of dissatisfaction with the scheme and has resulted in Coon's patches obtaining an (undeserved) unsavory reputation in certain quarters.

It is felt by the investigator that current schemes all leave something to be desired in terms of some or all of the following: user convenience; ability to adequately define the surface ability to obtain 'fair' lines (no scheme will satisfy everyone on this point); ability

to obtain intersections (various lines); and generally the ability to look at whatever information the user wishes to see. To be accepted and become the basis for hull surface representation valid for the entire process of preliminary design (either by perturbation of existing designs or ab initio design) through detail design, the above criteria must be met, as a minimum.

The investigator feels that the interface between the computer program and the user is of paramount importance. Of course, the best scheme available should be used to represent the ship hull surface. However, without logical, easy to use and understand "handles" for interacting with the computer, any scheme will be doomed to failure. The amount of data used to represent the hull may be transparent to the user, but is one aspect which has an adverse impact if it is too large since during detail design very large files must be accessed, manipulated and added to. One non-technical aspect of attempting to replace or refine an existing method or way of doing things was pointed out to the investigator by numerous persons. This is the fact that there are politics involved, since there is often a bias toward the status quo by certain personnel who may have been instrumental in bringing about the current process. This may extend through several layers of management, and the investigator has no suggestions for dealing with it, its existence being mentioned only to emphasize that not all problems involved here are technical ones.

3.0 Surface Schemes for Representation of Ship Hulls

Because of the ambiguity caused by the use of lines to represent ship hulls, it is necessary to use a surface definition scheme. In

addition, the data required to define the surface should be fixed (once the hull has been satisfactorily defined) and the amount not too large. There are several potential candidates for hull surface representation. None of them have the details completely worked out. We will discuss each of them briefly and comment on their suitability for implementation.

Kuo[6] describes a scheme using polynomials matched with cylinders generated by lines and circular arcs to describe a ship hull surface. The surface is divided into a number of regions, e.g., the midship cylindrical region, the forward region, the after region, and the stern region. While the scheme is touted by the author as one which automatically generates a fair surface, there seems to have been very little reported experience with the scheme. Indeed, there are few references to the book (which is intended to be a textbook) in the literature, and most persons asked during the course of the project had not heard of the book. It appears that the method may be feasible, but it probably does not lend itself to giving the user the types of interfaces which are desirable. This occurs because the coefficients in the representation are determined from continuity and matching of moments and other desired parameters of the ship hull. The investigator feels the scheme is probably not suitable for the above reasons, and is further somewhat skeptical of the claim that the hull surface will automatically be fair. The scheme would appear to be economical in terms of the amount of data required to represent the hull surface. It seems plausible that schemes involving few parameters would be easier to manipulate and be less likely to exhibit unfairness, however the lack of documented experience with the scheme leaves this idea only a conjecture.

The present lines scheme used in HULDEF could conceivably be extended

to a surface definition scheme by the use of suitable patches. There are potential and known drawbacks to this route. Foremost is the fact that HULDEF is not entirely acceptable in its present form for several reasons, including documentation, inability to obtain fair lines in many cases, and the fact that it is a batch program. The incorporation of patches would involve both rectangular and triangular patches and while there has been some discussion of this in the literature, there is some question as to whether the process is completely understood in terms of the compatibility conditions required to ensure smooth transitions across patch boundaries where rectangular and triangular patches meet. Also there is the previously mentioned bias on the topic of patches. The investigator does not feel this is the appropriate approach to take.

The use of Coon's patches has already been mentioned in connection with CASDOS in the previous section. It has been reported that the British Ministry of Defense is developing a surface representation scheme based on Coon's patches. Few details were available to the investigator, but reportedly bicubic patches are used and the surface is represented by very few patches, four in one instance. If this is possible, or even if considerably more patches had to be used, the amount of data required is certainly small enough. Further investigation of progress on this scheme is warranted.

Several schemes involve the use of spline functions and we digress for a brief discussion of splines and terminology associated with them. For our purposes, splines are piecewise polynomials (of odd degree) which have order of continuity one less than the degree, i.e., cubic

splines have continuous second derivatives. For simplicity we will deal only with cubic splines, the generalization to higher order being apparent. The connection with mechanical splines is given via the result that, of all functions $S(x)$ with continuous second derivatives and which pass through given points, (x_1, f_1), $i = 1,\ldots,N$, the "natural cubic spline" minimizes the integral $\int_{-\infty}^{\infty} (s''(x))^2 dx$, $s''(x)$ being approximately proportional to curvature. Here, "natural" refers to the fact that if $x \leq x_1 < x_2 < \ldots < x_n$ or $x > x_n$, $S''(x) = 0$, just as with the mechanical spline. Other end conditions are often imposed on mathematical spline functions. Various sets of functions may be used as a basis for representing spline functions.

(1) The <u>truncated power functions</u>

$$(x - x_i)_+^3 = \begin{cases} (x - x_i)^3 & , x \geq x_i \\ 0 & , x < x_i \end{cases}$$

are seldom used since they lead to computational difficulties. A linear function must be added for complete representation.

(2) The <u>cardinal splines</u> satisfy the Lagrange-type property, $S_i(x_j) = \delta_{ij}$, $i,j = 1,2,\ldots, N$, and are useful for representing the curves in terms of the function values, f_i. Again, for a complete representation, a linear function or other provisions must be included.

(3) The B-splines have the property of minimum support, i.e.,

$B_i(x) \neq 0$ only for $x_{i-2} < x < x_{i+2}$. Thus, changing a coefficient, b_k, in the representation of a curve, $\sum_{i=1}^{N} b_i B_i(x)$, results in a change to the curve only in the four adjacent intervals, (x_{k-2}, x_{k+2}), resulting in "local control". The points (x_i, b_i) define what are called "polygon control points", and do not lie on the curve. Special provisions must be made for B_1, B_2, B_{n-1}, and B_n.

In design work, curves and surfaces are usually represented parametrically, which simply means that each coordinate of the curve or surface is (in the case of spline representation) represented by a spline function. That is, a curve in the x-y plane is given by

$$x = S^{(x)}(t)$$
$$y = S^{(y)}(t),$$

where t is the parameter. Whether the functions $S^{(x)}$ and $S^{(y)}$ are given in terms of cardinal splines or B- splines has no bearing on the appearance of the curve, only on how the curve will be (or can be) manipulated.

Another approach to surface representation is discussed by Wu, Abel, and Greenberg [26]. Their method uses cross sections (control lines) represented by B-splines, then lofting cardinal splines are used to complete the surface between cross sections. Except for the fact that the lofting curves can only be manipulated indirectly, this scheme is similar, in a sense, to current lines schemes for hull representation. With this scheme all points on the hull surface have to be determined

by using (evaluating) one type of line. For example, think of the control lines as being made up of the body plan and the keel cross section. Waterlines or other lines running the length of the vessel (e.g., the isogirths used in HULDEF [29] might be appropriate, in which case, the keel line would be one) are then generated using lofting cardinal splines. To obtain any point on the surface requires evaluation of the appropriate lofting spline, and a body plan at a new station would be defined by its intersection with all lofting splines.

The above process is very similar to one used by Rogers, et.al., [36 and 41] in CAMILL, a program used to produce instructions for computer aided milling of wooden models. Principle differences are that several options are available for representation of the lines (each line has its representation form as a B-spline, cubic spline, or parabolically blended curve specified) and that waterlines and buttocks, as well as body plans, may be manipulated directly. It would seem that this scheme almost results in a surface representation by virtue of the large number of waterlines (the model cited in [41] had 89 waterlines, one every 6" on the full scale ship) needed for milling the model. However, it is not guaranteed that insertion of a new waterline would result in a fair line. The process described by Wu, Abel, and Greenberg might also be subject to this difficulty. This could depend on the choice of lines for the lofting cardinal splines to follow. The investigator feels these schemes are probably not suitable.

The use of parametric B-spline curves and surfaces have been investigated by a number of authors, e.g., Gordon and Riesenfeld [14], Rogers and Adams [22], Rogers [31], and McKee [42]. B-splines have a number of distinct advantages for the representation of ship lines and surfaces.

Among them are: they can be used to approximate given data very closely; it is possible to easily incorporate knuckles (discontinuous tangents at given points); one type of function can probably be used to represent the entire hull surface; local control of the curve or surface via the polygon control points; and predictable behavior of the curve or surface when a polygon control point is manipulated.

While a good deal of study of B-spline behavior has taken place, not all problems are solved, and this is particularly true of B-spline surfaces. The use of B-spline curves is well understood (see above references, for example) with the problems of manipulation of the curves and the appropriate display of information for interfacing with the user being solved problems. The problems of how to display appropriate information when the user is manipulating a surface rather than a curve is still under investigation. In two dimensions it is relatively simple to use the "rubber banding" technique to show both the old and new curves, and this gives the user a great deal of information about how his actions are affecting the curve. A similar device is desirable for surfaces, but the appropriate method for providing this information must be developed. Investigation of these matters is currently underway by Professor David F. Rogers at the Naval Academy, and perhaps by others as well.

4.0 Recommendations

The recommendations made by the investigator cannot be implemented in a short time span. A committment of effort over a period of some time and the acquisition of suitable computer hardware and supporting graphics equipment is required. While the cost of the equipment and

manpower is not negligible, the potential savings are great, and compared to the manpower and overall computational requirements for the design of a ship, are quite small. The effort required to integrate a new hull representation scheme into existing programs for detail design and numerical controlled manufacturing processes will depend on the nature of the current interface between present representation schemes and those programs.

The first recommendation is that the hull be represented as a surface. This is required for an unambiguous representation and to avoid having the hull change (however slightly) during the successive phases of preliminary design, contract design, and construction. This is particularly important in the latter stages, less so just after the preliminary design stage. The use of surfaces will enable the hull to be represented by fewer parameters which in turn should lead to less tendency for the lines to be unfair, in addition to requiring less storage.

It is the investigator's opinion that parametric B-spline surfaces are the best choice for representing the hull surface. Reasons for this are given in the previous section and are repeated here: they have good approximation properties; knuckles are easily incorporated by using repeated polygon control points; one type surface can represent the entire hull; local control of the surface via the polygon control points; and predictable behavior when a control point is manipulated. The polygon control points are not on the surface itself, and this has elicited comments expressing doubt as to whether designers would be able to accept and use them. The investigator believes that these doubts can be quickly dispelled with only a small amount of experience at an

interactive graphics terminal. The local control and (quickly) predictable behavior of the curve (or surface) will soon overcome any inhibitions possessed by the user.

In order to make full use of the advantages inherent in representing surfaces using B-splines, it is necessary to use interactive graphics equipment. Further, the graphics device must provide real time rotation, translation, and scaling in three dimensions. Zoom capability has been shown to provide matching of given data to within one part in 2^{16} [41] which corresponds to about 3/16 inch on a 1000 foot long ship. In addition, it is probably desirable to have available the capability of obtaining large scale plots of any of the various lines which the designer is interested in seeing. This latter capability need not be part of a dedicated facility, however.

The specific equipment mentioned here is meant to be indicative of the minimum capability that should be possessed by the facilities, and not an endorsement of particular brand names. A computer with the computational power and operating system capabilities on the order of the VAX 11/780 is required. Graphics equipment (several stations, at least, eventually) consisting of the equivalent of the Evans and Sutherland Picture System 2 along with supporting terminal, graphics tablet input device, and other supporting devices is needed. This equipment will allow interactive fairing of the ship hull surface, although detection of unfair portions of the surface can sometimes only be detected by construction of a model, as has been noted by Rogers [41]. Use of surfaces with a minimum of parameters, rather than lines should tend to avoid these problems, however.

Recent results have come to the investigator's attention regarding a scheme for investigating fairness of surfaces [43]. The scheme involves plotting curves of constant Gaussian curvature on the surface, and reportedly is very sensitive to small deviations on test surfaces. While the amount of computation required is fairly high, and thus a running check via the scheme is probably not feasible, it could serve as a very useful check for fairness in the final stages of the design process. Further results by Munchmeyer and his associates should be monitored.

The implementation of the required software will probably require several man-years of effort. Rogers [41] indicates that the entire CAMILL program involved a total effort of less than three man years. CAMILL involves many of the same kinds of ideas and operates on equipment similar to that required here. Personnel with the necessary qualifications to implement the required programs are on board at NAVSEA, and provided their time can be made available, will provide excellent software, in the investigator's opinion. Some developmental work in the area of appropriate interfaces with the user is required and this will involve some experimentation by several users to determine what works best. As such, this phase of the process can not be unduly hurried and it is worthwhile to point this out far in advance, as well as during the course of the project.

The investigator believes the above recommendations will enable the process of ship design (particularly) and construction for the U.S. Navy

(and others, potentially) to appropriately take advantage of available technology. While there are a limited number of ships being built, with relatively small amounts of the total expenditure going toward design (5%, according to [38]), the funds required here are really quite modest compared to the overall expenditure for even one ship, and would quite easily be recouped in terms of increased efficiency in the design process.

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